NdFeB Permanent Magnet Uses

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Rare earth element (REE) permanent magnets (NdFeB) are a critical element in a vast and growing number of industrial applications. In consumer electronics, a broad category encompassing computer, CD, and DVD hard drives, in addition to the ubiquitous cell phones, the nominal NdFeB magnet content may be small, but the global market share for this sector accounts for almost 30% of NdFeB demand, due to a large and continually increasing consumer base. It is estimated that wind turbines that primarily employ permanent magnets will add roughly 110 GW annually of on- and off-shore capability over the next few years. Electric vehicles (EVs) and E-bicycles (EBs) equipped with permanent magnet motors comprise the transportation contribution. Permanent magnet motors have garnered nearly 100% of the market share among EV manufacturers worldwide. Industrial, professional service, and personal robots, most using permanent magnets, are also included in the projected global need for rare earths, particularly Nd and Dy.

rare earth elements | permanent magnet | electric vehicles | electric bicycles | wind turbines | robotics | consumer electronics | dysprosium | neodymium | NdFeB

1. NdFeB Permanent Magnets

NdFeB magnets (also called rare earth, REE, NIB, Neo or just neodymium magnets) are permanent magnets produced using rare earth alloys [1]. They possess stronger magnetic fields than other available permanent magnets, for example ferrite (Fe) or aluminum nickel cobalt (AlNiCo) magnets [1]. An REE magnet is made from an alloy of Nd, Fe, and B. The name reflects the major elements but is not inclusive, as Dy (dysprosium) and sometimes Tb or Gd are added to retain coercivity at high temperatures. **Table 1** summarizes the relative compositions of these magnets, which are used to calculate the demands of Nd and Dy in this research.

Table 1. NdFeB magnet content by element with REEs highlighted, reflecting relative composition utilized in this research, data adapted from Peak Resources [2].

NdFeB Elements	Weight Percent
Iron (Fe)	64%–68%
Neodymium and Praseodymium (NdPr)	29%–32%
Boron (B)	1%–1.2%
Dysprosium (Dy)	0.8%–1.2%
Niobium (Nb)	0.5%–1%

NdFeB permanent magnets were independently and simultaneously discovered in 1984 by both General Motors (melt-spun nanocrystalline $Nd_2Fe_{14}B$) and Sumitomo Special Metals (full-density sintered $Nd_2Fe_{14}B$) [3]. The high raw material acquisition cost of their predecessor (samarium cobalt (SmCo) permanent magnets) was the driver for the research [3]. NdFeB magnets continue to be the strongest commercially available permanent magnets. Their maximum energy product is very high relative to Fe, AlNiCo, or SmCo permanent magnets [4]. The maximum energy product is a measure of the magnetic energy that can be stored per unit volume of a magnetic material [4][5]. Specifically, it is calculated as the maximum product of the material's residual magnetic flux density (or degree of magnetization) and its coercivity (its ability to resist heat and demagnification after it is magnetized) [4]. The high power-to-volume ratio increases efficiency, allowing for the miniaturization of NdFeB magnets while retaining a much better performance than the Fe or SmCo species [6]. Furthermore, these properties make it possible to miniaturize high-capacity motors. A myriad of industrial and consumer products that depend on the superlative performance of

NdFeB magnets include actuators, anti-lock braking systems and other automotive parts, audio equipment, communication systems, frictionless bearings, magnetic storage disks, magnetic resonance imaging (MRI), robotics, and more [6][7][8]. NeFeB batteries are used in National Defense systems, including guided missile actuators and ship propulsion systems and infrastructure [9]. These magnets are employed in electric and hybrid vehicles and, increasingly, in wind turbines. Due to the increasing demand across a multitude of sectors, the NdFeB magnet market is expected to see significant growth [1].

Clean energy, electrification, automation, and electronic devices are critically dependent on rare earth permanent magnets and, hence, the elements Nd and Dy, as well as Tb and samarium (Sm) [7]. The major categories driving NdFeB magnet growth are EVs, wind turbines, robots, and consumer electronics. The present usage and projected growth are included in a CAGR, along with the material intensities for estimating future Nd and Dy demand through 2050.

2. Wind

Wind turbines vary in generating capacity, drive mechanism, and generator type. For those using direct-drive gearing with a permanent magnet generator, large-, medium-, and small-scale versions contain 650 kg, 160 kg, and 80 kg of NdFeB, respectively [10]. The total rare earth content is ~30% as the reduced metal [11][12]. Conversion to the oxide requires a stoichiometric factor, along with an estimated 20% loss in conversion from oxide to metal, not including the metal loss during magnet fabrication [7]. Dy is included for high temperature stability and improved coercivity [11][13]. Though percentages greater than 6%–10% are desirable, cost and availability have pushed the Dy content to ~4%, with advanced manufacturing methods striving for an even lower content overall [13][14]. Notably, not all wind turbines use permanent magnet generators, but the market share of those that do is increasing due to the higher conversion efficiency and reduced maintenance, a desirable pairing for off-shore wind turbines operating at low speeds [15][16].

Wind turbines have a wide variety of systems for operation, mostly consisting of geared/gearless transmission accompanied by either electromagnet or permanent magnet (PM) generators, where gearless transmission is direct-drive (DD) [17]. Low-speed generators, usually associated with DD, often utilize electromagnet or PM generators. Notably, the magnet mass in these generators depends on their speed, with the increasingly preferred low-speed generators often requiring larger quantities of PMs [17]. Surveying across four manufacturers, Moss et al. (2013) reported an average range of 0.625–0.85 tons/MW [17]. However, this range was reported for low-speed PM generators. For the analysis, the researchers use an average of 0.5 t of magnet per MW, taking into account the aforementioned analyses and ranges in addition to a recent study determining the average among all turbines to be around 0.5 t [18]. At this material intensity and with a REE content of around 30%, the Nd and Dy contents for this research are taken to be 29% (145.5 kg/MW) Nd and 1% (4.5 kg/MW) Dy, representing mid-range estimates [17]. For geared-EM systems, which can use either PM or EM to start the generator, an equal share between the two is assumed.

Wind turbine installation has seen considerable growth throughout the past few years, with China's share at 46% overall in 2015, 56% on-shore and 50% off-shore in 2020, 42% on-shore and 80% off-shore in 2021, and 47% on-shore and 58% off-shore in 2022, as reported by the global wind energy council (GWEC) [19][20]. While China dominates the off-shore installations, countries within Europe are also increasing theirs, with the Netherlands accounting for between 4 and 25% of off-shore installations throughout the years [19]. The United States, on the other hand, has held steady at between 15 and 18% of the total with on-shore installations only [19][20]. Growth within the wind turbine energy industry has been record-setting in recent years and continues to show substantial CAGRs for the next several years. Annual on-shore installations have contributed between 35 and 87 GW of additional capacity per year over the past 10 years, with 2020 showing an almost 62% growth from the previous year [19]. The off-shore installation rate remained steady through most of the past decade, ranging from 1.6 to 6.9 GW per year through 2020, but in 2021, the additional capacity installed was 21.1 GW, a nearly 200% growth [19]. For additional information on other market growth predictions within wind energy.

After some record-setting years, wind turbine growth is predicted to remain steady at a somewhat lower rate over the next decade. The GWEC predicts an on-shore growth rate of 6.1% and an off-shore rate of 8.3% [19]. Starting in 2020, with 837 GW on-shore and 57 GW off-shore capacity, the GWEC estimates annual capacity increases of 75 GW on-shore and 6 GW off-shore through 2026 [19].

These projections form the basis for calculating PM demand and the required amount of REO, presented in this research as the baseline demand. However, the market share of turbines using PM generators is expected to change through 2050; it is generally expected to increase for on-shore turbines and decrease for off-shore turbines, mostly due to optimization and implementation [21]. JRC predicts low and high growth scenarios for both turbine types, where low demand results in an increased market share for on-shore and decreased for off-shore [21]. A high-demand scenario suggests that the off-shore share will remain the same while on-shore demand will nearly double. For comparison, the baseline study assumes a 50% market share to demonstrate an average value between possible scenarios.

The JRC Science for Policy Report, which covers low- and high-demand scenarios, explains that these market shares were based on GHG emissions limitation goals predicated on the Paris Agreement, as well as innovations in the industry for low demand, while high demand is based on lower maximum temperature goals than the Paris Agreement [21]. Low-demand estimates expect on-shore turbines to increase from 32% to 40% by 2050, while off-shore decreases from 76% to 41% [21]. Their high-demand scenario predicts that on-shore increases from 32% in 2020 to 68% in 2050 and off-shore maintains an industry permanent magnet market share of 76% through 2050 [21]. As these are some of the primary factors driving the wind turbine market to increase, further analysis is presented through other predictions. The IEA lays out more aggressive growth in many industries, including wind turbines, within the next decade to achieve the NZE by 2050 goals. To reach these goals, the IEA suggests a total wind power capacity of over 3000 GW in 2030, resulting in a CAGR between 18 and 19% for the industry, which translates to a needed annual installation growth two to three times greater than the current predictions [22].

3. Electric Vehicles

The existing market share among all automotive manufacturers illustrates the superiority of permanent magnet motors. Tesla, for instance, shifted from using alternating current (AC) induction motors to direct current (DC) permanent magnet motors for their drive trains in 2017 [2][23]. In 2022, Tesla was responsible for 2%–3% of the worldwide NdFeB magnet demand (excluding micromotors, sensors, and speakers) [24]. Other manufacturers are continuing to expand their electrification plans. In 2020, 90% of new EV registrations came from the top 20 global manufacturers, of which 18 have begun to widen their portfolios while scaling up production of light-duty EVs [25]. There were over twice as many light-duty EV models available in 2022 (500 models) than in 2018 [26]. Currently, NdPr motor technology is utilized in ~99% of all passenger EVs, representing a ~99% market share for NdPr permanent magnet motor solutions, a trend that should continue for the foreseeable future [2]. The availability of heavy-duty EVs is also broadening, with four major truck manufacturers indicating an all-electric future, according to the IEA in 2022 [27]. Collectively, the top three markets (China, Europe, US) have 500, 120, and 170 commercial bus and truck models available, respectively [26]. Supporting these plans, global consumer spending on EVs peaked at 383 billion USD in 2022, with governments contributing nearly 43 billion, bringing the total spending to ~425 billion USD. This was a 50% increase in total spending relative to 2021 [26].

EV sales increased significantly in 2020. Europe saw the highest growth, bringing their total to 3.2 million EVs, although China's EV fleet is still larger, totaling 4.5 million [27]. EV sales in the United States have continued to break records over the past few years compared to 2018, which represents the onset of increased demand for EVs [28]. For instance, 2021 sales in the United States exceeded 600,000 units, an estimated 75% increase from 2018 [29].

The global EV stock hit 10 million in 2020, which was a marked 43% increase from the previous year [29]. Two thirds of the new EV registrations and stock were battery electric vehicles (BEVs) [27]. As EVs become more popular, they can compete on a total cost-of-ownership basis in certain countries. Moreover, fiscal incentives, offered by some countries, have buffered EV purchases from the downturn in car markets [27]. These represent just a few of the many factors contributing to the huge uptick in EV sales in 2020. In 2022, new EV sales alone exceeded 10 million and are projected to increase an additional 36% in 2023, bringing the year-end sales total to 14 million EVs [26]. Three markets continue to dominate the EV market (in order of sales): China, Europe, and the United States [26]. Notably, China accounts for 60% of new EV sales and has over half of the EVs on the road today [26]. Europe saw a 15% growth in 2022, translating to a 20% EV market share, and the United States experienced 55% growth, or 8% of the market share [26]. Sales in India, Thailand, and Indonesia experienced 300% growth collectively, largely due to incentives and policy support schemes to encourage EV adoption by the public [26].

The baseline growth scenario in this analysis takes into account the aforementioned historical growth, along with other factors, including overall economic growth and climate incentives, in addition to EV turnover rates and the availability of REOs based on recent mining production. A vehicle turnover rate of 12 years gives a CAGR of 6%. Given the recent market data and predictions, this is unrealistically low. REO production from 2015 to 2022 (as reported by the USGS) saw annual growth varying from 2% to 20%, with a significant production increase of over 40% from 2017 to 2018; that same year also saw a substantial EV sales increase of over 60% [30][31][32][33][34][35][36][37][38]. Thus far, REO production has kept up with the overall REO demand across sectors; however, because of the projected growth in both the implementation of these technologies and in public demand, it is likely, according to Adamas Intelligence [39][40], that demand will overtake supply by as soon as 2030. Notably, the recent boost in EV sales (more than doubling from ~3 million in 2020 to ~6.5 million in 2021 and increasing over 50% from 2021 to 2022, with over 10 million units sold), makes the EV market a significant contributor to future REO shortages [41]. However, prior to this substantial increase, EV sales growth throughout the next decade was projected at anywhere between 4.5% and 24.7% [6][42]. Factoring in the replacement rate, recent sales, and REO availability, this research, therefore, sets the baseline CAGR at 9%.

The use of permanent magnets in vehicles is not limited to EVs. Today's light gasoline-powered vehicles already use rare earth permanent magnets for power steering, power door locks, power window lifts, cruise control, automatic mirror positioning, fluid pumps and sensors, electric brake actuators, and power seats, among many other uses. One study found that mid-class internal combustion engine vehicles utilize permanent magnets in over 30 separate applications [2], while other studies have found over 100 of these applications [6][43]. Some reference all of these PMs as NdFeB magnets, while others, based on a detailed analysis of four selected vehicles, list only a few functions (e.g., speakers) that incorporate NdFeB magnets, while the others use Fe or SmCo magnets [2][44]. As most of these (now standard) "accessories" are likely to carry over into EVs, their contribution to PM demand is effectively constant as declining gasoline/diesel passenger vehicles are offset by the corresponding increases in EV sales. In the former, the named applications represent a total NdFeB magnet mass of ~0.6 kg, aside from the engine [2]. The few select functions identified, namely, speakers, by a more detailed analysis were found to be as high as 0.114 kg [44]. However, the traction motor of a battery-powered EV contains an additional ~1.5 to 2.5 kg of NdFeB magnet. This number varies. It is sometimes difficult to discern whether the mass listed refers to PM or rare earth mass. Using the upper values, (including oxide-to-metal conversion and magnet manufacturing losses) the approximate demand for pure NdPr oxide is calculated at 40% of the final NdFeB magnet weight. Each new EV, thus, translates into a 1 kg increment to NdPr oxide demand [2][44][45][46]. Using an overall PM demand per vehicle of 2 kg results in a Dy oxide demand of 0.17 kg, representing 8% of the final weight of the NdFeB magnet [45][46].

As climate goals and incentives heavily influence this industry, other scenarios were included to provide a comparison to the baseline scenario given above. One market growth prediction expects EV sales to overtake sales of internal combustion engine (ICE) vehicles by 2047 as a result of these other factors [47]. The IEA outlook runs through the year 2030 with a few scenarios, including the stated policies scenario (STEPS) and the sustainable development scenario (SDS) [48]. STEPS accounts for limitations in growth alongside goals for each country, and SDS focuses closely on overall energy goals [49][50]. Limitations considered in STEPS include the market, infrastructure, and overall finances as they pertain to each country's pledged energy goals. STEPS projects annual EV sales by 2030 to be over 25 million, whereas SDS predicts over 46 million [40]. Bloomberg and Wood Mackenzie base their projections on economic trends. Bloomberg's economic transition scenario (ETS) states that 60% of new vehicle sales will be EVs, and Wood Mackenzie expects new EV sales in 2050 to reach 62 million [47][51].

4. Electric Bicycles

EBs also contribute significantly to REE demand as a transportation sector. The material intensity is far less per unit than for EVs; for this research the researchers use 0.2 kg as compared to 2 kg per EV unit [6][46]. Of the 0.2 kg, the material intensity for Nd is calculated at 30% of the magnet, or 0.06 kg per unit, while Dy is 4% of the magnet, or around 0.008 kg per unit [6][46]. While the material intensity is minimal compared to other industries, the overall demand is still impactful given recent global trends in EB sales. As EBs are not generally considered a necessity in terms of new technology implementation for the sake of climate change in comparison to other sectors, sales projections are based more on the social and economic implications. Past predictions showed low growths, some as low as 2.95% [6], but similar to EVs, recent sales increases have some firms forecasting CAGRs through 2030 to be anywhere between 5% and over 15% [52][53][54][55][56]. As with the EV analysis, REE production was considered alongside other predictions of some markets reaching saturation, as well as the top sales market in China showing predictions of slowing down [52][53]. The resulting baseline CAGR is estimated at 5%, taking into consideration further predictions that by 2050, the overall EB fleet may be around 2 billion with around 80 million sales per year [53], as reported in the Electric Bike Worldwide Report [54][55].

5. Robots

An overlooked sector that is heavily dependent on REE magnets is robotics. This industry varies from industrial grade robotics to personal consumer robotics, and NdFeB magnets are a critical element of both, mostly used in sensors, actuators, internal motors, and to ease the movement of parts within. According to the International Federation of Robotics (IFR), industrial robot sales reached 383,500 units in 2020 with a CAGR of 9% for the period 2015–2020 (or 11% for 2016–2021), with higher rates forecast [57][58]. Industrial robots (IR) are employed in industrial automation, such as those utilized in vehicle manufacturing, and they may be either in-place and fully stationary or have mobile capabilities, often programmable. An additional 131,800 professional service class robots, which include medical and cleaning robots, for example, were added in 2020 for use in the non-manufacturing and manufacturing sectors, representing a 14% increase in this robotic class [57]. The current CAGR forecasts reported by IFR lie around 10% and are predicted to drop to 7% before 2025 [58]. Between this and the recent growth varying between the aforementioned 9 and 11%, this research assumes a CAGR of 10% [57][58]. The NdFeB content for an industrial robot is estimated to be ~15 kg per robot, which translates in the researchers' analysis to approximately 6 kg of NdPr oxide and 0.19 kg Dy oxide, considering conversion losses [2]. Peak Resources also reports relevant market shares for industrial robots to be around 50% [2]. At a reported 50% market share, sales in 2020 result in NdPr oxide and Dy oxide demands of 1213 and 37.50 metric tons, respectively. By 2050, the annual NdPr oxide and Dy oxide demands are predicted to reach 21,174 and 655 metric tons, respectively, should the industry continue growing as it has been.

In addition, according to the IFR, sales in the private sector, represented as service robots (SR) in this research, reached 19 million robotic solutions in 2020; these robots account for personal use, including mobility assistance robots and cleaning devices [57][58]. As the robots in this sector are much smaller than others, the magnet content is less, although the estimated market share is ~70% [2]. The NdFeB content of these robots is estimated at 0.6 kg per unit [2]. NdPr and Dy oxide weight is then calculated to be around 0.24 kg and 0.01 kg, respectively. Factoring in the 2020 sales, the total demand when accounting for the stated 70% market share is 323 metric tons of NdPr oxide and 10 metric tons of Dy oxide. For this sector of robots, a 7.5% CAGR is assumed when considering the recent and forecasted growth from the IFR, resulting in a 2050 demand of 2826 tons of NdPr oxide and 87 of Dy oxide [57][58].

6. Consumer Electronics

The consumer electronics industry relies heavily on permanent magnets for a multitude of products, including hard disk drives, motors for printers and scanners, and a variety of other products, including appliances and fan motors in loudspeakers and computers, to name a few [1]. With the increasing demand for cloud computing, which requires centers where data can be stored, hard disk drives contribute to REE demand [1]. The reported PC shipments in 2020, according to Statista, totaled 214 million units globally, increasing to 328 million units in 2021 [59]. Other growth and demand for magnets throughout this industry can be attributed not only to growing populations but also to the development of certain regions, such as the Asia Pacific region [1][60].

For the class of magnet in consumer electronics, the NdPr content is 28.6 wt.% and the Dy content 1.4 wt.% [42]. Tablets, notebooks, and hard drives are estimated to have 0.06 g Dy content and 1 gm Nd content, the exception being HDDs with 2 gm per unit [61]. Overall, consumer electronics are estimated to consume 29.4% of global NdFeB magnet production, i.e., 35.1 kt in 2020, with the potential to consume 8.7% or 65.4 kt in 2050 [42]. This projected growth results in a 2% global CAGR, considered a high-demand scenario at the time of publication; however, other predictions and metrics show it may be slightly higher or lower than the baseline 2% growth [42]. High- and low-demand scenarios were based on general population growth projections, as well as economic circumstances leading to greater development across certain parts of the world, influencing a greater demand for GCE. For instance, developing markets, such as the aforementioned Asia Pacific region, contributed significantly to a higher CAGR through 2028, between 5% and 15.6% [60][62][63]. The high-demand scenario in this research was set at 3.5% to account for the longer term, whereas low demand is set to 1%, closely following population and GDP growth predictions [64][65].

7. Industrial and Non-Drivetrain Motors

In 2020, industrial motors constituted the second-largest source of total U.S. demand for NdFeB magnets at 30%, surpassed only by consumer electronics at 45% [9]. Globally, industrial motors dominated at 30%, followed by consumer electronics [42]. With the uptick in wind turbines (off-shore specifically) and EVs/EBs dominating the market share projections through 2050, industrial motors and non-drivetrain motors represent a smaller share, although their NdFeB magnet consumption will continue to increase. For instance, in 2020, non-drivetrain motors in vehicles used 9.4 kt of NdFeB magnets, representing 7.9% of the market share, whereas projections for 2050 foresee an increase by over a factor of three (29.3 kt) with a market share of only 3.9% [9].

Industrial (permanent magnet) motors can be DC or AC and are further classified as asynchronous/synchronous [66]. Industrial motors can be used for any process that requires power or motion. Non-drivetrain motors in vehicles consist of any motor that is not contributing to the motion of the vehicle [67]. Examples of these include the motors found in power windows, windshield wipers, power seats, power mirrors, etc. [44]. NdFeB magnets allow for motor miniaturization, which is ideal for many automotive applications.

Due to the limited availability of information on industrial motor/non-drivetrain motors in vehicles, the researchers adopted a CAGR of 2.9 and 3.9, respectively, calculated from 2020 to 2050, and reference values of 36.0 and 9.4 kt, respectively, given the total NdFeB magnet weight, from the DOE [42].

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